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## Update on Results of SPRE Testing at NASA Lewis

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Prepared for the  
26th Intersociety Energy Conversion Engineering Conference  
cosponsored by the ANS, SAE, ACS, AIAA, ASME, IEEE, and AIChE  
Boston, Massachusetts, August 4-9, 1991



(NASA-TM-104425) UPDATE ON RESULTS OF SPRE  
TESTING AT NASA LEWIS (NASA) R D CSCL 100

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creasing the displacer seal clearance. A series of tests were performed, starting with the baseline seal radial clearance, with an incremental increase in the clearance until it produced a significant measurable effect on PV power and/or PV efficiency. Therefore, tests were performed with the baseline clearance of 2 mil (0.002 inch), and 3, 4 and 5 mils nominal displacer seal radial clearance. The clearance was changed by grinding the very hard chrome oxide coated outside diameter of the displacer base, with a diamond wheel, to achieve the desired radial clearance with the cylinder. Figure 3, a photo of the displacer, shows the area on the base which was ground to adjust the seal clearance. Care was taken to ensure concentricity of the ground surface to the displacer bearings. Typical measured total runout of the ground surface, with the displacer assembled and rotated in its bearings, was less than 0.2 mils.

#### Results:

Figure 4 shows the effect of the displacer seal clearance on the measured PV power with the engine operating at 2.0 temperature ratio and 15 MPa. Experimental data is shown for both 8 and 10 mm piston amplitudes. The HFAST code predicted values shown are for 9 mm piston amplitude based on a displacer/piston amplitude ratio of .933 and 81° displacer phase angle relative to the piston motion. The actual measured values for displacer/piston amplitude ratios, for the 8 and 10 mm piston amplitude points, ranged from ~1.03 to 1.15 and values for displacer phase angles ranged from 79.36° to 80.2°. The PV power tended to slowly diminish as the displacer seal clearance increased, and this change in PV power agreed reasonably well with the predictions. The measured power at the design condition (2.0 temperature ratio, 15 MPa mean pressure, and 10 mm piston amplitude), with 5 mil clearance was ~505 W lower than the power observed with 2 mil clearance. Using linear interpolation to adjust for a 10 mm piston amplitude, the code predicted ~456 W lower power.

The measured and predicted effects of increased displacer seal clearance on the PV efficiency is shown in Figure 5. There was no apparent change in measured PV efficiency with increased displacer seal clearance, which disputes the code prediction of a very significant efficiency drop. It should be noted that, in

2. develop a correlation model for the piston mid-stroke position based on the experimental data,
3. determine the effects of the piston centering port area on PV power and efficiency.

#### Test description:

The SPRE piston has two sets of mid-stroke centering ports as illustrated, schematically, in Figure 6. One set of centering ports, located at the compression space end, connects the compression space to the gas bearing drain plenum. The second set of ports, which is located at the gas spring end, connects the piston gas spring to the gas bearing drain plenum. For these tests, only the effects of the centering ports on the compression space end of the piston were investigated. These ports, shown in the photo in Figure 7, are L-shaped passages consisting of equally spaced holes, located near the outer diameter of the piston, which are drilled axially from the compression space end of the piston and intersect with radially drilled holes through the outer diameter. These ports can easily be blocked off by installing a set screw in the compression space end of the passage, which is threaded.

The centering port tests were run concurrently with some of the displacer seal clearance tests, and were performed after the displacer cylinder was modified by adding the groove for the seal ring. Therefore, the clearance seal data with 2 mil displacer clearance, both with and without the displacer seal installed, were used for baseline references with 6 piston centering ports open. Tests also were performed with 4 centering ports, without the displacer seal, and with 3 and 2 centering ports open, with the displacer seal installed. For all tests, the plugs were arranged so that the open ports were equally spaced for flow symmetry. These centering port tests were performed with the engine operating over a wide range of conditions, where the temperature ratio varied from 1.6 to 2.0, the mean pressure varied from 5 to 15 MPa, and the piston amplitude varied from 6 to 10 mm.

#### Results:

correlation method also was used for the data taken with 4 and 3 centering ports. The first order curve fits for each set of data are shown in Figure 11. The slope of the lines is very sensitive to the number of open ports. The correlation coefficients (slopes) determined for each set of data are plotted versus the number of ports in Figure 12. The data points fall in nearly a straight line indicating that the slopes for each set of centering port data are proportional to the number of centering ports raised to approximately the -0.775 power. Although this correlation approach is crude, it provides a way to estimate the effective stiffness or spring rate of the centering ports, which is proportional to the reciprocal of the correlation coefficient. The effect of the centering port stiffness was somewhat apparent while performing these tests. As the number of ports was reduced, the piston mid-stroke position had a greater tendency to wander, especially at the higher power points.

The effect of the number of centering ports on PV power and efficiency was obscured by having the displacer seal installed for part of the tests, and the raw data results tend to be scattered and conflicting. Table 1 compares the measured PV power and efficiency at the design operating condition for 6 and 4 centering ports without the displacer seal, and for 6, 3, and 2 centering ports with the displacer seal. Installing the displacer seal produced a 318 W decrease in PV power and efficiency increased by 0.139 points for the baseline with 6 ports. The HFAST code predictions, based on the actual measured operating conditions, but not adjusted for the number of centering ports also are shown. The measured values can be compared after normalizing, by subtracting out the predicted values ( $\Delta$  PV power and efficiency). Reducing the ports from 6 to 4, without the displacer seal ring installed, decreased the PV power 100 W and PV efficiency increased 0.211 percentage points. With the displacer seal ring installed, reducing the number of ports from 6 to 3 produced a 50 W decrease in PV power and a 0.148 point decrease in PV efficiency, while the PV power increased ~500 W and PV efficiency increased by 0.726 percentage points by reducing the ports from 6 to 2.

#### CONCLUDING REMARKS

The results of the SPRE displacer seal clearance tests suggest,

that since the Stirling cycle power is only mildly degraded by increasing the displacer seal clearance, and the cycle efficiency appears to be insensitive, in the range which was tested, the design clearance and tolerances for the displacer could be increased. This would reduce fabrication costs and relieve some of the concern about maintaining close running clearances for long operating periods.

Although the test results are conflicting and strongly influenced by the presence of the displacer seal ring, it appears that a modest increase on both PV power and efficiency may be achieved by reducing the piston centering port area. It should be pointed out that reduction in the number of piston centering ports will be accompanied by a decrease in the effective centering port stiffness, which can impact the dynamic response and stability of the system.

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TABLE 1 - EFFECTS OF THE NUMBER OF PISTON CENTERING PORTS AT THE DESIGN POINT

CENTERING PORTS	DISPLACER SEAL RING	PV POWER MEASURED (KW)	PV POWER PREDICTED (KW)	$\Delta$ PV POWER (KW)	PV EFF. MEASURED (%)	PV EFF. PREDICTED (%)	$\Delta$ PV EFF. (%)
6	NO	12.568	12.139	0.429	19.279	18.520	0.759
4	NO	12.395	12.066	0.329	19.476	18.506	0.970
6	YES	12.144	11.821	0.323	19.418	18.326	1.092
3	YES	11.649	11.376	0.273	18.759	17.915	0.844
2	YES	12.514	11.682	0.832	19.849	18.031	1.818

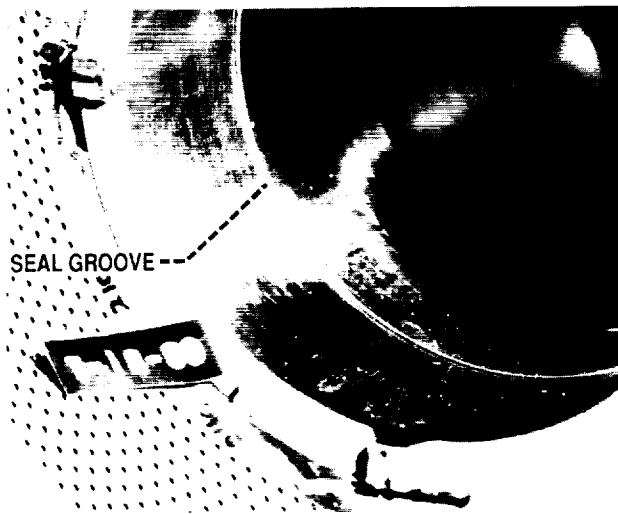


FIGURE 1. DISPLACER CYLINDER MODIFICATION.

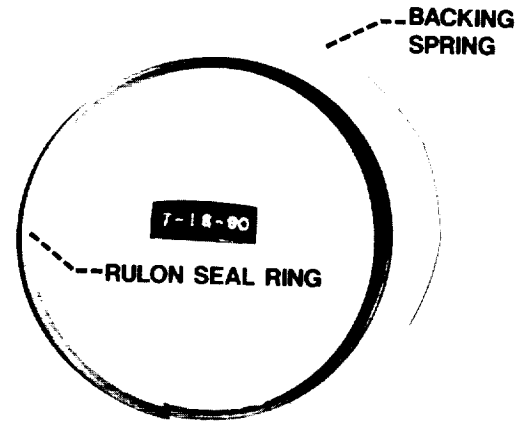


FIGURE 2. DISPLACER SEAL.

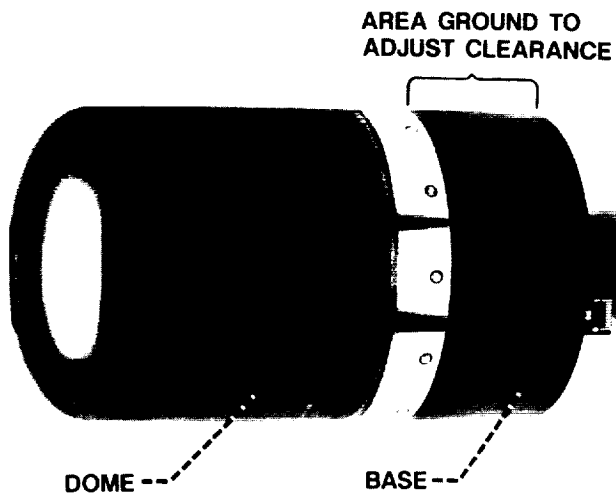


FIGURE 3. SPRE DISPLACER.

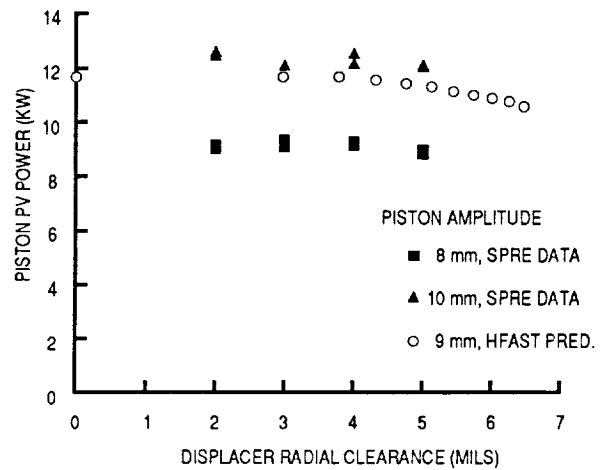


FIGURE 4. EFFECT OF THE DISPLACER SEAL CLEARANCE ON PV POWER AT A TEMPERATURE RATIO OF 2.0 AND MEAN PRESSURE OF 15 MPa.

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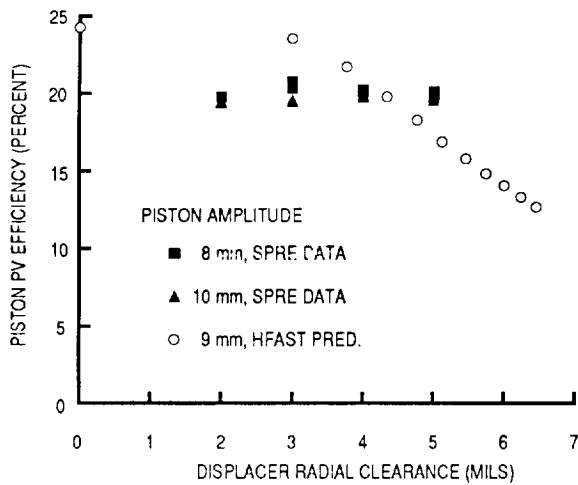


FIGURE 5. EFFECT OF THE DISPLACER SEAL CLEARANCE ON PV EFFICIENCY AT A TEMPERATURE RATIO OF 2.0 AND MEAN PRESSURE OF 15 MPa.

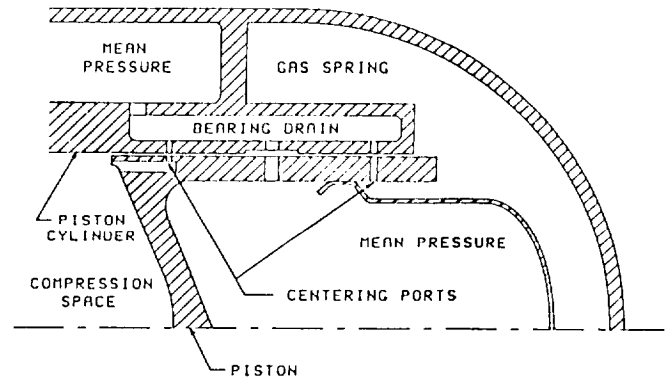


FIGURE 6. SPRE PISTON CENTERING PORTS.

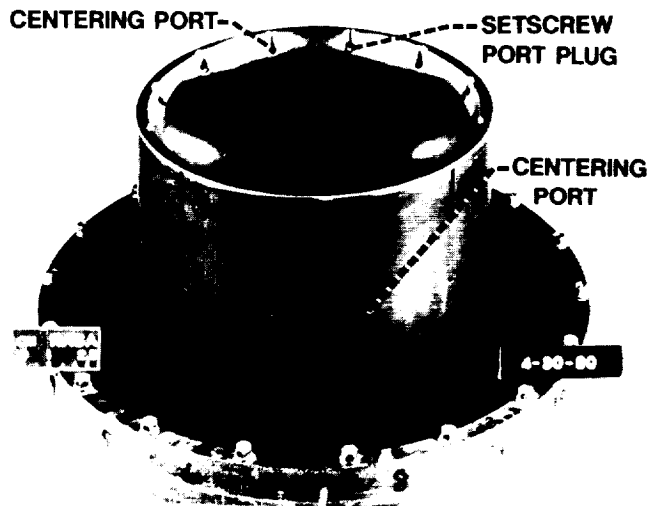


FIGURE 7. POWER PISTON ASSEMBLY

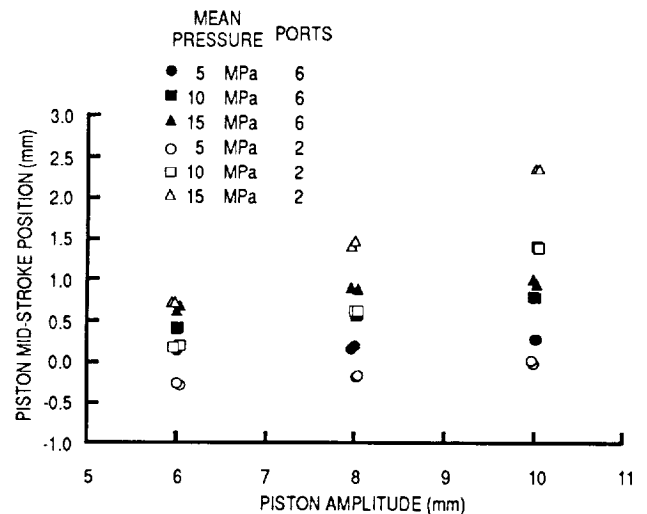


FIGURE 8. MEAN PRESSURE DEPENDENCE OF THE PISTON MID-STROKE POSITION AT A TEMPERATURE RATIO OF 2.0.

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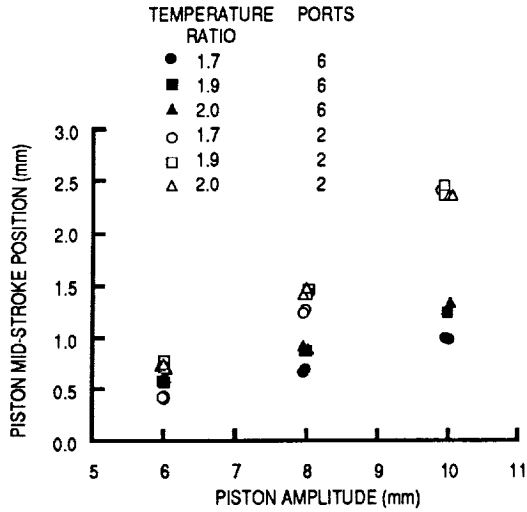


FIGURE 9. TEMPERATURE RATIO DEPENDENCE OF THE PISTON MID-STROKE POSITION AT A MEAN PRESSURE OF 15 MPa.

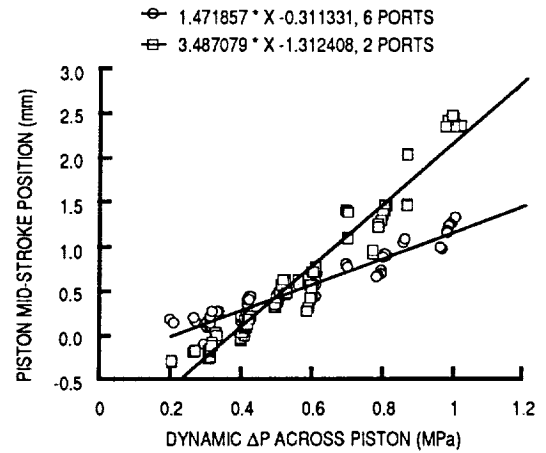


FIGURE 10. PISTON MID-STROKE POSITION AS A FUNCTION OF THE DYNAMIC  $\Delta P$  ACROSS THE PISTON

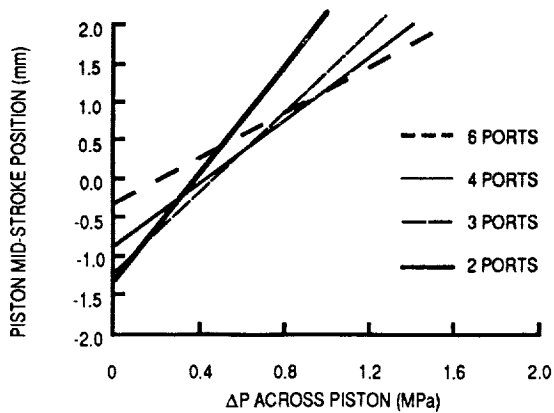


FIGURE 11. FIRST ORDER CURVE FITS OF THE DATA WITH 6, 4, 3, AND 2 CENTERING PORTS OPEN.

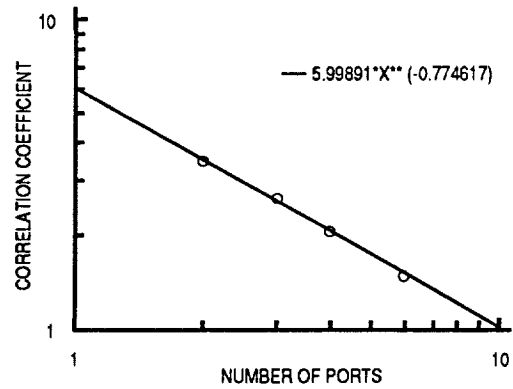


FIGURE 12. DEPENDENCE OF THE CORRELATION COEFFICIENT ON THE NUMBER OF OPEN CENTERING PORTS



National Aeronautics and  
Space Administration

## Report Documentation Page

1. Report No. NASA TM-104425		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Update on Results of SPRE Testing at NASA Lewis				5. Report Date	
				6. Performing Organization Code	
7. Author(s) James E. Cairelli, Diane M. Swec, Wayne A. Wong, Thomas J. Doeberling, and Frank J. Madi				8. Performing Organization Report No. E-6258	
				10. Work Unit No. 590-13-11	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the 26th Intersociety Energy Conversion Engineering Conference cosponsored by ANS, SAE, ACS, AIAA, ASME, IEEE, and AIChE, Boston, Massachusetts, August 4-9, 1991. James E. Cairelli, Diane M. Swec, Wayne A. Wong, and Thomas J. Doeberling, NASA Lewis Research Center; Frank J. Madi, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142. Responsible person, James E. Cairelli, (216) 433-6142.					
16. Abstract The Space Power Research Engine (SPRE), a free-piston Stirling engine with a linear alternator, is being tested at NASA Lewis Research Center as part of the Civilian Space Technology Initiative (CSTI) as a candidate for high capacity space power. This paper presents results from recent SPRE tests designed to investigate the effects of variation in the displacer seal clearance and piston centering port area on engine performance and dynamics. The impact of these variations on PV power and efficiency are presented. Comparisons of the displacer seal clearance test results with HFAST code predictions show good agreement for PV power, but show poor agreement for PV efficiency. Correlations are presented relating the piston midstroke position to the dynamic $\Delta P$ across the piston and the centering port area. Test results indicate that a modest improvement in PV power and efficiency may be realized with a reduction in piston centering port area.					
17. Key Words (Suggested by Author(s)) Stirling engine Free-piston Displacer seal clearance Piston centering ports			18. Distribution Statement Unclassified - Unlimited Subject Categories 20 and 44		
19. Security Classif. (of the report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 8	
				22. Price* A02	

